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CIRCULARITY MEASURING SYSTEM
A Shape Gauge Designed Especially for Use on Large Objects

by
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Abstract. The Circularity Measuring System (CMS) was designed and is currently used to match the shapes of the redesigned Solid Rocket Motor's field joints during assembly in the Vehicle Assembly Building (VAB) at Kennedy Space Center, Florida. It is a fully developed mechanism used for the assembly of launch vehicles.

The CMS's development was unique for two reasons. First, it is an unusual solution to an original problem. The problem is to mate high-tolerance, large, flexible structures. The immediate (or obvious) solution is to measure radii from an approximate center. This proved to be operationally unfeasible, since the device to accomplish this required a complicated and lengthy setup and was sensitive to environmental change, especially temperature. A less obvious solution was to determine shape. Because the cases had been measured on a rotating table at the manufacturer's facility and again prior to casting propellant, they had already been matched to achieve the proper interference fit. Therefore, matching the shape is all that is required at final assembly. Determining shape could now be done with a bridge gauge, originally conceived as measuring arc heights and matching the corresponding points on each mating surface. This allowed the development of a highly portable, easily used device.

The second unique feature is the symbiosis of the bridge gauge with a personal computer. The data collected from the bridge gauge are used by the computer with a unique algorithm to piece together the arc segments generating the shape with a resolution of 30 ppm.

The bridge gauge (see Figure 1) has arms with two fixed end points, the distance between which is precisely 914.4mm (36 inches). An outwardly, spring-loaded probe slides along the perpendicular bisector of the line between the fixed points and measures small displacements within 0.0025mm (0.0001 inch). Roll and pitch sensors help the technician to level the gauge for maximum accuracy. Pins can be attached to the arms near the end points and to points near the probe, to mate with guide holes (if provided) in the object to be measured.

The technician measures the displacements at a sequence of positions around the circumference of the object. This could be done most conveniently by using the guide pins and indexing to a circumferential string of guide holes. The measured displacements are sent to the computer. For each measurement, the portion of the measured surface between the end points can be approximated by the circular arc tangent to the end points and to the end of the probe. The computer calculates the arc for each measurement. It pieces together the arcs from the sequence of measurements to obtain a curve consisting of circular-arc segments that approximate the measured surface (see Figure 2).

Briefly, the algorithm works by smoothly joining circular arcs of specified curvature. Because the curvature data are approximate, a linear parametric deformation must be performed to generate a smoothly closed shape. A natural extension of the algorithm allows it to incorporate corners and be used to approximate unclosed curves in the plane. It is shown that the algorithm exhibits invariance under the Euclidean transformations, preserves convexity, and has convergence properties.

The shape gauge has been extensively tested against a radius-measuring device and photogrammetry, with the National Bureau of Standards in observance. It successfully demonstrated a repeatable accuracy of 0.10mm (0.004 inch) on a 3.7m (146 inches) diameter.

The bridge gauge and its associated computer constitute a system that measures the out of roundness of large cylinders. Currently the system is being developed to determine the shape of any continuously curved surface.

Intended originally for use on the Solid Rocket Motors of the Space Shuttle, the system has been demonstrated determining the preservation of circularity of submarine hulls. The system can also be used to measure the straightness or roundness of complex geometric shapes, such as aircraft or hulls of ships. Development of the device continues as a NASA "spin-off" for industrial and commercial use.

The requirement to measure the Redesigned Solid Rocket Motor (RSRM) field joint to a previously unnecessary accuracy precipitated the design of the Circularity Measuring System (CMS). The redesigned field joint has a modified tang, incorporating a capture feature; this also provides an interference fit (Figure 3). During the engagement of the joint, this capture feature must not be plasticly (permanently) deformed or the interference fit will not be preserved. To verify that the RSRM segments achieve the interference fit properly, the position of the o-ring sealing surfaces of the joint must be known relative to a common centerline within 0.076 mm (0.003 inch). This determination is made by Thiokol at the Wasatch facility. The Wasatch facility determines the selected fit of the segments in each rocket motor assembly. These measurements are made in the case of a new segment while on the turning machine (thus the center point of the radii is known with some assurance). In the case of a refurbished segment, the measurement is made on a massive rotating table with a linear displacement reading taken from an external known position. In both cases the environment is controlled or at least stable and monitored so thermal expansion can be accounted for.

These measurements are completed prior to the cases being cast with propellant, turned on their side, transported by rail to Florida, removed from the transport, stored vertically, and then finally moved to the Vehicle Assembly Building for assembly. The case and propellant behave as a viscoelastic structure. The empty case having the same stiffness properties as a soft drink can with the ends cut off; the propellant having about the same density as the eraser on the end of a pencil. The propellant has properties similar to creep and appears to have a "memory." That is, it will return to a previous state, probably the state which caused the most internal stress. The point to be made is that while the circumference measurement has not changed, the casings certainly are not round.

In fact, our tests showed that they assume a tri-lobed shape sometimes referred to as "bread-loafing." Also, the cases have different properties: the forward and aft are stiffer because they have domes attached, and the two center segments are open at both ends. The aft segment has stiffener rings on its lower half increasing its stiffness, and the forward segment has the propellant star pattern for its core where the others are cylindrical. Thus each case has a different stiffness. To say that since the segments are all exposed to same environments they ought to deform the same is incorrect, since they all have different physical properties. The bottom line is that the segments must be measured prior to assembly in Florida after transit.

We determined that the segments were flexible enough, especially in the small displacements we were looking for, and that the handling and other associated equipment would cause deflections of sufficient magnitude to be unacceptable. We found the deflections inputted at the lower end of a segment were transmitted to the upper but inverted. The major axis at the bottom was now the minor axis at the top. This was attributed to the factory joint (a localized area of increased radial stiffness) in the center of each segment behaving as a fulcrum. It was also shown that this same phenomenon occurred when the segments were suspended from a lifting fixture; however, the loads then were imparted to the top, causing an inverted reaction at the bottom. A further complication occurs because the aft segment (the first in the assembly) is supported on four spherical bearings (a statically indeterminate load case), which are aligned on intersecting axes 60 and 120 degrees apart. Because of the four-point support, the loads into the structure need not be equal. The lifting beam which supports the suspended mating segment is also a four point fixture (again an indeterminent load case), but these four load points are on two axes, 90 degrees apart. Thus the perturbations in the radial shape caused by the handling and support equipment do not necessarily coincide.

To summarize, the goal is to determine the relative position of the tang and clevis at corresponding radial locations to within 0.076mm (0.003 inch). The segments have preserved their circumferential measurement. Thus the interference fit of the selected assemblies is conserved if the shapes can be made nearly identical. Transportation and handling alter the shape, and the physical properties of the segments vary.

There were various methods investigated to effect the field determination of shape. These will be discussed briefly. First was the process that was used prior to the RSRM design, that is to measure diameters. This process used a surveyors tape graduated in two (2) cm. increments, which was converted to British units for data recording and the data entered to the nearest 0.001 of an inch (0.025 mm). This technique was grossly flawed due to rounding errors, and was abandoned. Next a 3.7 m (146 inches) inside micrometer was used. Trying to determine shape by measuring diameters is not accurate because the assumptions that the end points and the center are in line, and the end points are equidistant from the center cannot be guaranteed. "Inspection & Gaging," Kennedy & Andrews, Industrial Press, pps. 272, 456-461, gives an excellent discussion of why this technique is wrong. An example is the Wankle rotor, where the measurement of points on the circumference 180 degrees apart are equal, which can give the appearance to be diameters. It is not until the realization that the center is not equidistant from the ends that the shape then becomes tri-lobed (which interestingly enough is the peculiar condition of the RSRM segments).

The obvious solution is to measure radially from a point that approximates the center. A tool was designed and tested; it has been referred to as the radius arm tool. Demonstrations of the radius arm tool showed an operational difficulty in that it is a complex assembly which must be installed on both the stationary and suspended sides of the joint. To effect this operation on the permanent scaffolding in the VAB required considerable time assembling and disassembling the tool. The sweep of the radius could not be manual, since varying angular velocity, axial, and tangential loads caused by human power created unacceptable errors. The device has a motor-driven sweep which is also indexed to relay angular position when the linear voltage displacement transducer (LVDT) is cued for a reading. To make the device such that it could be transported and assembled manually, it is primarily aluminum and therefore sensitive to temperature. The VAB is an unconditioned hangar. This inability to have a controlled environment in the VAB renders this tool useless in this assembly area. Additionally, the repeated assembly and disassembly of this tool as well as the relatively dirty work area would cause the bearings of the tool to wear, thus reducing the resolution of the tool.

Commercial techniques were canvassed, finding the most suitable system to be photogrammetry. It has the resolution to achieve the 0.076 mm (0.003 inch) target. The flaw is that it takes a minimum of four (4) hours to process the data from the measurement. Because of the viscoelastic properties of the casing, in four (4) hours time the case shape will change.

The criteria for an operational tool were becoming evident: it must not require a controlled environment, it must minimize moving parts, it must be portable, and it must deliver immediate data results following the measurement (obviously some innovative thinking was in order here). Existing commercial systems of sufficient accuracy had a minimum of a four (4) hour wait to process data. The radius arm tool was not accurate in the VAB environs as well as being difficult operationally to use.

A purely mechanical device was tested (labeled the comparator). These devices were a block with two (2) dial indicators which simultaneously measured the tang and clevis while they were in close proximity (just prior to engagement). Six (6) or more units were used simultaneously about the circumference of the joint. These were unsuccessful at making the measurement because of the pendulum motion of the suspended segment. Also since the measurement had to be made with one segment suspended immediately above the other it was all but impossible operationally to alter the segment shape by a shaping device or redistribution of loads in the lifting beam cable drops.

From this tool another criteria was learned. The determination of clevis-to-tang gap cannot be made relative to one another in the VAB assembly environment.

Traditional or typical solutions to the measurement were not working. A completely different approach had to be taken since it did not appear sweeping a radius or determining run-out was workable. A feature independent of radii had to be found. The hypothesis presented was that instead of making a direct comparison of radial displacement we could compare arc heights from a fixed chord and extrapolate the displacement measurement from these readings. The tool could be a convenient length set by the chord. It would be portable and have only one moving part. Because of its compactness, thermal expansion and contraction would not significantly affect the measurement (so a controlled environment is not necessary). Data reduction would be immediate, especially if a personal computer is used as a data logger and processor. The tang and clevis can be measured independently. Thus all the criteria which caused the previous tools to be ineffective could be overcome.

The original hypothesis was expanded because the item intended to be measured, the curve, is continuous (approximates circular). Two adjoining arcs of different radius on a continuous curve share a common tangent at their adjoining point. With this geometric fundamental, the arc radius which can be calculated from the chord and arc heights can be connected. With the circumference data (which has not changed since determined very accurately at the Wasatch facility), a very accurate approximation of the shape can be achieved. This approximation was shown to be repeatable to within 0.10mm (0.004 inch) under various conditions in numerous qualification tests.

The beauty of this tool is its sheer simplicity. It has already been described concisely in the abstract; further description for this paper's purpose does not seem warranted. The tool is completely documented by drawings, design manual, mathematical proof, operation and maintenance manual, as well as a compilation of tests performed.

Briefly, there were two major qualification tests preformed. The first was in the VAB at Kennedy Space Center where the micrometer and the CMS were tested using photogrammetry as a control. As stated previously with one independent measurement to scale upon a circumference or major chord (apparent diameter), the CMS determines absolute shape repeatable to 0.10mm (0.004 inch) on a 4m. (12 ft.) diameter. If all that is required is a shape comparison (as is the case of the RSRM assembly), then the independent measurement is unnecessary.

The fact that the CMS measurements can be used without a secondary independent measurement is key to its usefulness during SRM assembly. This ability has been demonstrated by test. The following logic exercise also demonstrates this ability.

> The selective fit of the mating segments has been previously determined very accurately with the fit defined as an interference fit. Therefore, if the two shapes are the same within a tolerance band, the segments will mate. Again this has been determined elsewhere and need not be repeated at final assembly. The SRB mate is a peculiar case in that the shape is very nearly circular and the center line of the segments nearly coexist. With these initial conditions, all we need to know is the deviation from circularity of the tang and clevis. CMS provides that set of data. Subtract the deviations from circularity for the tang and clevis at matching radial positions, and you get a distribution of delta circularity data. If the spread of this data does not exceed a quantity derived from the design tolerances of the interference fit, then the joint can be made. Please note this determination does not require that the circumference or radius be known at assembly. All that must be known is that the selective fit determination has been accomplished and you have the right segments to be mated. This argument has been presented for an interference fit but it also holds for a running fit or match fit.

The second series of tests occurred at Marshall Space Flight Center comparing the CMS with the radius arm tool again using photogrammetry as a control. The National Bureau of Standards was in observance. Again CMS demonstrated its repeatability to 0.10mm (0.004 inch). This test was key in the CMS being accepted as the comparison gage for segment mating at KSC. Its ease of use, portability, and insensitivity to temperature all demonstrated its superiority over the other devices for this application.

The CMS has been demonstrated as an alternative device to determine hull circularity of a submarine at the Portsmouth Naval Shipyard. Here we learned how the maritime industry has wrestled with the problem of determining shape. The standard practice is to go to the lofting room and scribe an arc on a sheet of aluminum that exceeds the radius of the hull by a known distance. This template is then positioned against the hull with surveying equipment and using a small scale measure from the scribe line to the hull. This must be done at multiple frames along the hull. Each frame requires its own template. Each boat is different enough to require a dedicated set of templates. The Navy is acutely aware of the thermal distortion problems; so they attempt to make the measurements in the early morning, before sunrise when ambient temperature is most stable.

The CMS determination of deviation from circularity matched previous template trends, and its ease of use impressed the shipyard, but further development for the tool for this application has not occurred. However, this is going to be investigated as an area for future commercialization. The possible commercial applications seen today are assembly of large tankage, inspection of bulk storage tankage, lofting, flatness, and straightness determination.

Assembly of large tankage has problems very similar to the RSRM. Take the example of welding an end dome to the cylindrical section of a large tank. A standard practice is to start at one point and continue around until back at the beginning. Then any misalignment will be cumulative and concentrated at the point of closure. Normally, this misalignment is not great enough that the gap can not be drawn back together. But this causes residual stress which can be an undesirable situation. If better matching of the joint is possible so that the weld can be made in distributed beads, then the residual stress could be eliminated, reducing possible failure modes.

Since the CMS is portable, it could be used as an inspection device looking for local bulges or cavitation indicating weak areas of the walls. Periodic inspections of bulk storage tanks might mitigate the risk of repeating the accident occurring in the summer of 1989 when bulk storage ruptured in the northeast of the United States, spilling its contents into an adjoining waterway.

As a device to do or inspect lofting, the CMS is well suited. Previously discussed was our demonstration on a submarine hull. From this it is possible to extend to surface vessel hulls as well as to any cross-sectional shape (e.g., aircraft fuselages and wing frames, etc.).

The tool can also be used in an inverse way from previously described applications to determine straightness or flatness (planarity). This would be useful in tooling or track alignment. All possible uses of the tool can not be fully defined. It can be used to determine convex, concave, or combined curvatures. With modest improvements, it can be enhanced for commercialization.

One of the areas which has been investigated as a product improvement is the elimination of the electrical umbilical between the instrument and its computer. The alternative is to use a small datalogger system employing Eprom's or similar devices. The datalogger would be programmed from the host computer, disconnected to make the measurement with the instrument, then reconnected to determine the shape. Another area of further development is the evolution of the algorithm to allow for nonclosure of the curve being measured. An algorithm has been developed for this purpose, but it needs revision for more general application.

Summary

The CMS was developed to make an in-situ determination of shape similarity for selected fit large cylinders (RSRM segments). It does this to a repeatable accuracy of 0.10mm (0.004 inch). This is less than goal of 0.07mm (0.003 inch) but was determined adequate because of the addition of an assembly aid that increased the entry chamfer of the clevis side of the joint. The usefulness of the CMS is demonstrated by the application to measurements other than its specific design purpose, such as submarine hull circularity, SRM mid-case circularity, as well as circularity of interfacing SRM tooling, specifically the rounding devices and horizontal disassembly devices.

Commercialization of the tool is being pursued, since it is an enhancement of metrology technology for circularity determination. The most accurate in-situ technology it replaces is determination from a template. The CMS is an improvement in accuracy and operation.

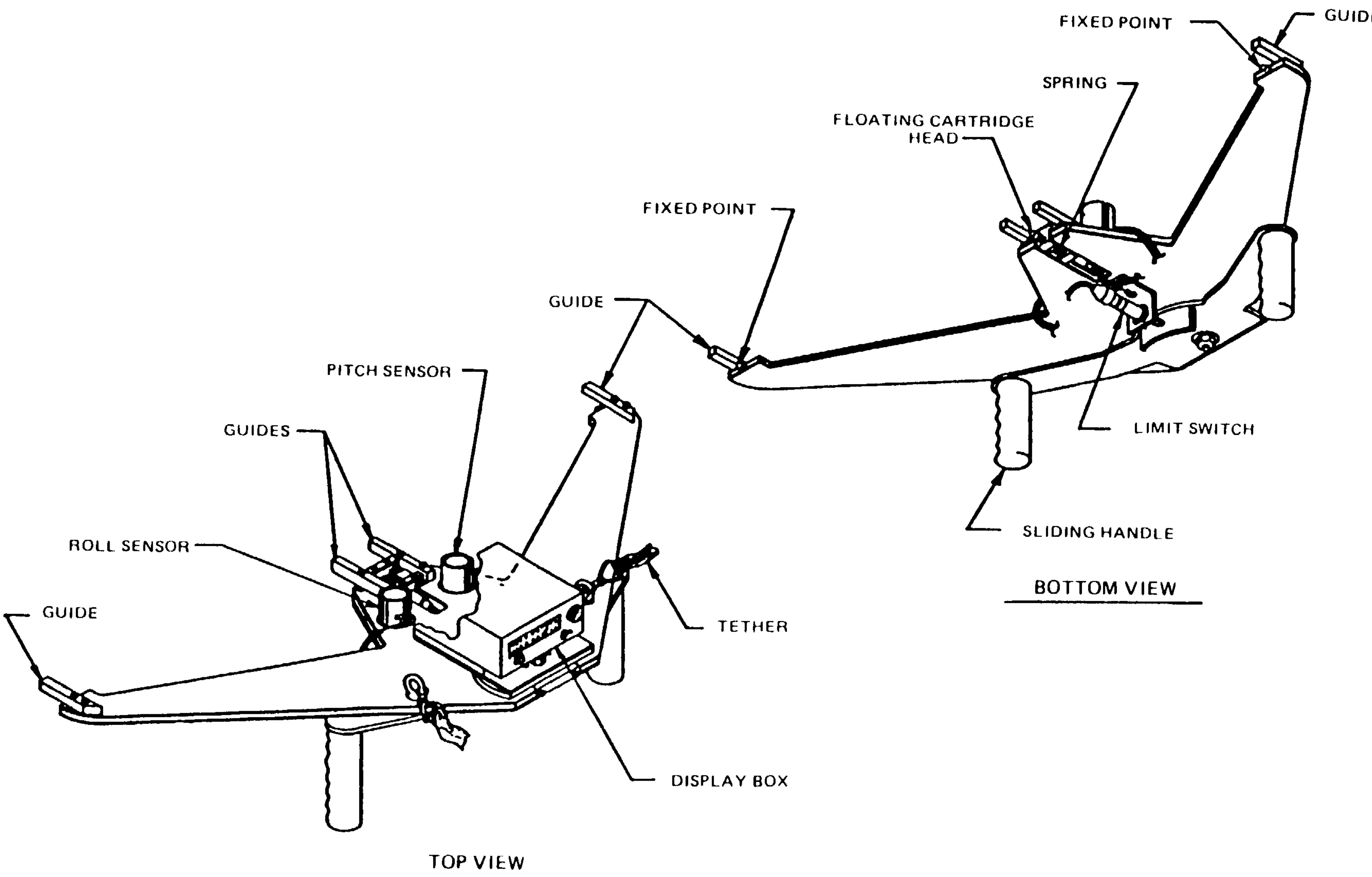
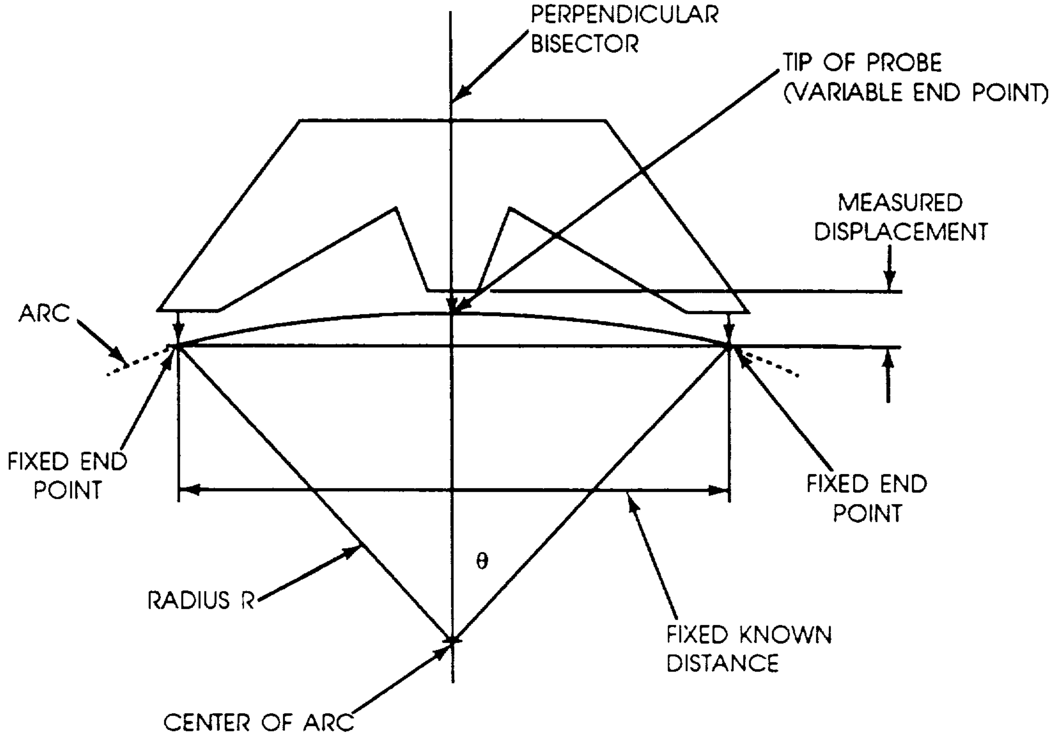
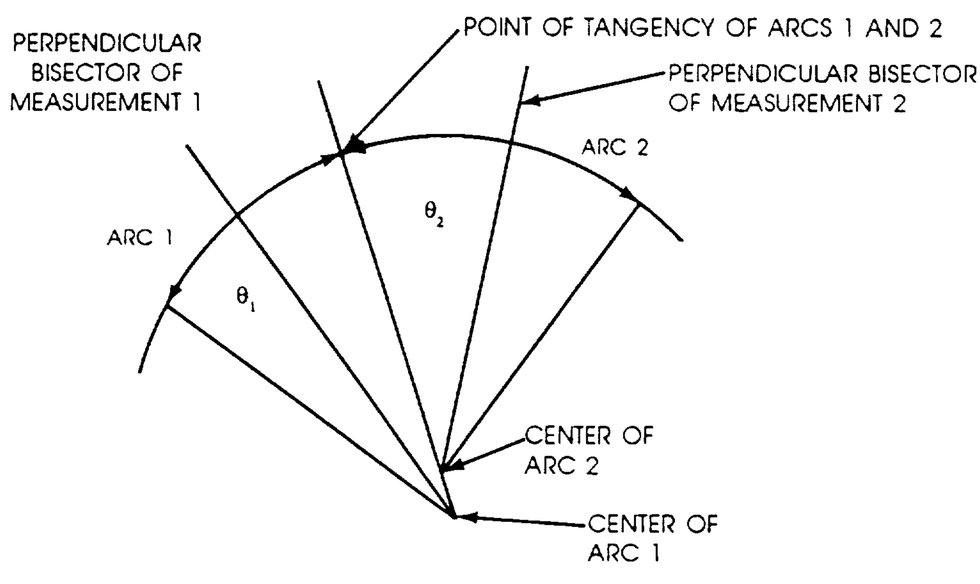


FIGURE 1. CIRCULARITY MEASURING DEVICE SYSTEM SHAPE GAUGE



CONSTRUCTION OF ARC FROM MEASUREMENT



CONNECTION OF ARCS

FIGURE 2

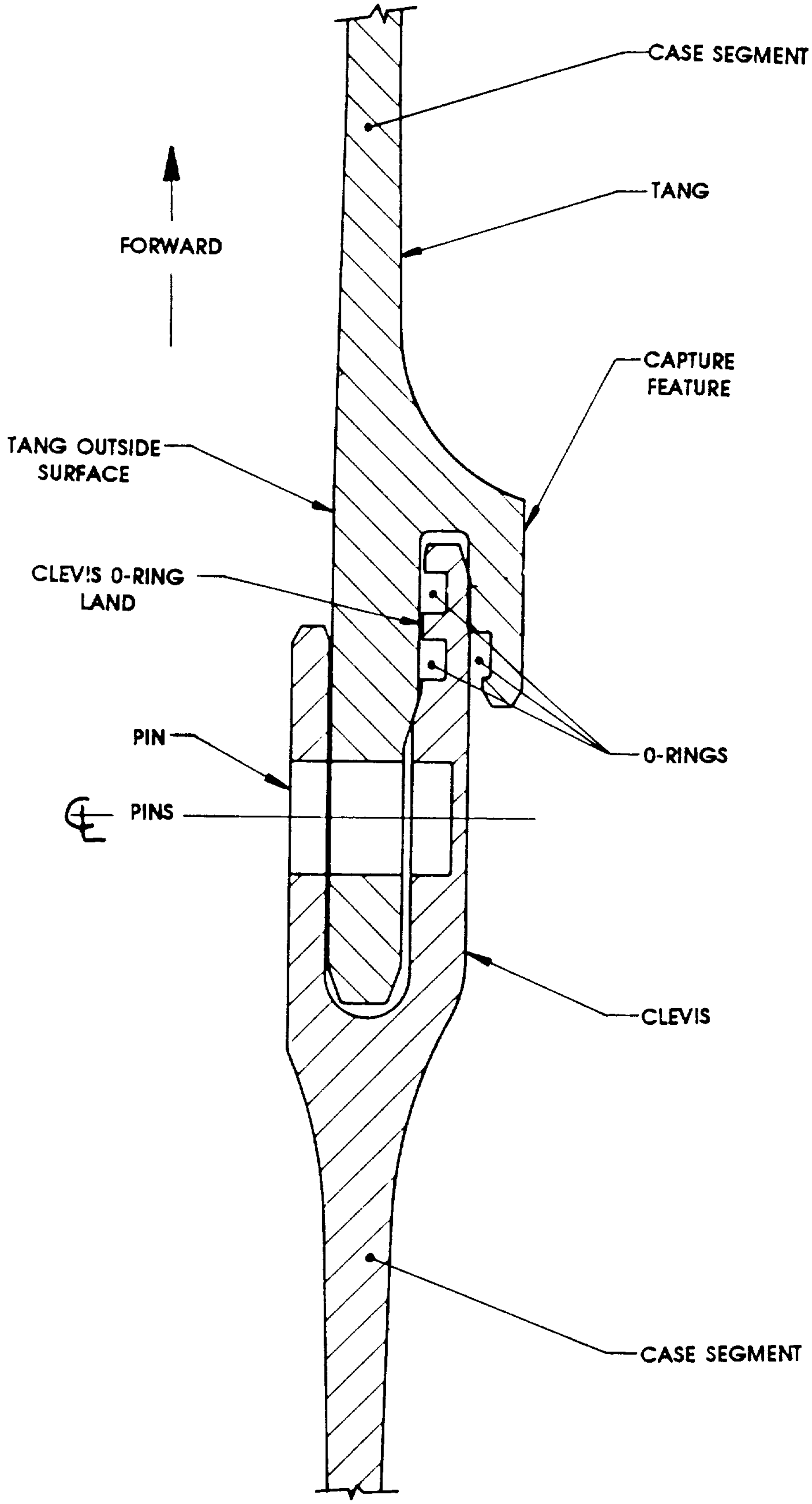


FIGURE 3. RSRM JOINT